BURIED EXPLOSION MODULE (BEM): A METHOD FOR DETERMINING THE FRAGMENT HAZARDS DUE TO DETONATION OF A BURIED MUNITION

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ABSTRACT

During unexploded ordnance (UXO) remediation operations, ordnance may be found that is deemed unsafe to move. In this case, the ordnance must be destroyed in place. In order to protect the disposal personnel as well as the public, a withdrawal distance from the detonation is enforced. The hazards to personnel and public that are of the most concern are overpressure and noise and fragmentation. For most unexploded ordnance the fragmentation range is much larger than the inhabited building distance (IBD) for overpressure.

The Structural Branch of the U.S. Army Engineering and Support Center, Huntsville (USAESCH) has developed an analytical method to calculate public and operational personnel withdrawal distances for fragmentation of buried munitions. The method addresses cratering and soil ejecta effects as well as primary fragmentation from the munition.

The Structural Branch has developed software to simplify and standardize the calculations to determine the withdrawal distance due to fragmentation and soil ejecta due to the detonation of a buried munition. This software which is called the buried explosion module (BEM) has been incorporated in the Mapping Explosive Safety Hazards (MESH) software.

The theory used in the development of the BEM software will be discussed. The software will be outlined and an example presented.

1.0 INTRODUCTION

The U.S. Army Engineering and Support Center, Huntsville (USAESCH) has developed an analytical method to calculate public and operational personnel withdrawal distances for buried munition disposal. The buried explosion module (BEM) is a program designed to be used to calculate the residual velocity of fragments produced by a buried munition and the maximum ejecta radius of large soil chunks produced by the buried explosion. BEM is

Report Documentation Page	Form Approved OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **AUG 1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Buried Explosion Module (BEM): A Method for Determining the Fragment Hazards Due to Detonation of a Buried Munition**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineering & Support Center, Huntsville,ATTN: CEHNC-ED-CS-S,P.O. Box 1600,Huntsville,AL,35807-4301**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001002. Proceedings of the Twenty-Eighth DoD Explosives Safety Seminar Held in Orlando, FL on 18-20 August 1998.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

designed to be used in conjunction with the computer software TRAJ [1] to calculate the fragment trajectories.

The theory used in BEM is discussed. The input required for the software is detailed and two example problems are given.

The results from the BEM software are compared to the results obtained by applying the method by hand. USAESCH is involved in a test program to determine the thickness of sandbags necessary to defeat the primary fragments from a munition detonated on the ground surface. The results from the BEM software for mitigation of primary fragments by tamped earth are compared to the results of the sandbag tests completed to date.

1.1 BACKGROUND

An analytical method to calculate public and operational personnel withdrawal distances for buried munition disposal has been proposed by Huntsville Center (HNC) to the Department of Defense Explosive Safety Board (DDESB). The method includes cratering calculations and calculations of the velocity of the fragment as it exits the soil using equations from DOE/TIC 11268 [2], and fragment trajectory calculations using TRAJ [1]. The maximum ejecta radii of large soil chunks produced by the cratering are calculated using Figure 5.20 in DOE/TIC 11268 [2].

In order to simplify and standardize the fragment calculations, new computer software (using this method) called BEM has been developed. This software is described in the following sections.

2.0 THEORY

As a buried munition explodes fragments are produced which travel through soil before escaping to the air and presenting a hazard. The soil slows down the fragments and, in some cases, may stop the fragments completely. In most cases the explosion causes a crater. Soil from the crater is also thrown away from the center of the explosion becoming hazardous. However, if the munition is buried deeply enough a camouflet is formed instead and no soil is ejected from the site. The question becomes how much soil does the fragment have to penetrate before escaping and what is the density of this soil?

Preliminary calculations for a variety of munitions show that by a distance of one foot from the center of the explosion, the fragment velocity is approximately twice that of the soil particles. Which suggests that for at least a portion of the burial depth the fragment is travelling through undisturbed soil. However, it is not clear at this time for which portion of the burial depth this is true. Therefore, as a conservative estimate, all of the soil is assumed to have a density of one-half its undisturbed density for the purposes of calculating the drag coefficient on the fragment velocity.

2.1 FORMATION OF CRATER OR CAMOUFLET

Whenever a buried explosive charge is detonated, a cavity or void is formed within the soil. If the energy release is relatively close to the surface, the cavity or void vents to the atmosphere and a crater is formed. If the energy release is sufficiently deep below the surface a void, called a camouflet, is formed. Equations 5.19 and 5.20 from DOE/TIC 11268 [2] are used to determine whether a crater or a camouflet is formed.

$$X = 4.605 + \ln\left(\frac{W^{1/4}}{d}\right)$$

$$Y = [6.438 + 1.398(\ln(\frac{W^{1/3}}{d}))]\tanh^5[2.00 + 0.4343(\ln(\frac{W^{1/3}}{d}))]$$

where W = the explosive weight in pounds
d = the depth of burial in feet.

If X is greater than Y, a camouflet will be formed. If X is less than Y, a crater will be formed.

2.2 FRAGMENT VELOCITY

The maximum fragment weight and initial velocity are calculated as described in Chapter 2 of TM 5-1300 [4] and detailed in HNC-ED-CS-S-98-1 [6]. Due to calculation restraints (division by the depth of burial), if the depth of burial is zero the software assumes a depth of burial of 0.1 ft. If the depth of burial is zero (surface burst) the fragment does not pass through any soil and the velocity of the fragment is the initial velocity. Otherwise, the fragment velocity as it exits the soil is calculated using equation 6.3 from DOE/TIC 11268 [2].

$$V_s = V_0 e^{-12k_v R}$$

where V_s = fragment velocity at a distance R from the center of detonation (ft/sec)
V_0 = initial (maximum) fragment velocity (ft/sec) (using the Mott-Gurney equation, equation 2-32 from TM5-1300)
R = distance from the center of detonation (ft) = depth of burial
k_v = velocity decay coefficient

$$k_v = (A/W_f)\gamma_0 C_D$$

where A/W_f = fragment form factor, the ratio of the presented area of the fragment (in^2) to the fragment weight (lb). A standard fragment is assumed.
γ_0 = specific weight of the disturbed soil = ½ the specific weight of the undisturbed soil (lb/in^3)

C_D = drag coefficient (dimensionless) = 0.6 for V > 1100 ft/sec for spinning chunky fragments

V_s is used to calculate the fragment trajectories using TRAJ [1]. The line of sight angle from the depth of burial to the edge of the crater is calculated to determine the start angle for TRAJ. Using Equation 5.22a from DOE/TIC 11268 [2], the true crater radius is calculated.

$$R_T = 2.155 \cdot d \cdot \left(\frac{W^{1/3}}{d}\right)^{0.865}$$

Where R_T = the true crater radius (ft)
d = the depth of burial (ft)
W = 1.2 x TNT equivalent explosive weight (lb)

$$\text{Start Angle} = \tan^{-1}\left(d/R_T \right)$$

Using the fragment velocity as the fragment exits the soil, the fragment weight and the start angle, TRAJ [1] is used to calculate the maximum horizontal range of the fragment.

2.3 MAXIMUM EJECTA RADII

As the crater is formed, large chunks of soil are expelled and become potentially hazardous fragments. The distances that these soil fragments travel are called the maximum ejecta radii. These radii are shown in Figure 5.20 of DOE/TIC 11268 [2] (see Figure 1). The line shown in this figure has been specified by an equation and this equation has been included in BEM. Representing the values on the horizontal axis by the variable x and the values on the vertical axis by the variable y, the equation for the line becomes

$$y = 10^{(0.9 \log x + 1.11)}$$

$$x = \frac{W^{7/24}}{\rho^{7/24} c_p^{1/3} g^{1/8} d}$$

where W = explosive yield (lb) = 1.7 x 10^6 x 1.2 x TNT equivalent explosive weight (lb)
ρ = soil mass density (lb-sec^2/ft^4)
c_p = seismic velocity of the soil (ft/sec)
g = gravitational constant (32.2 ft/sec^2)

Figure 1 was developed from results of cratering experiments reported in AFWL-TR-74-351 [5]. The soil ejecta radii from Figure 1 are based on 2- inch diameter (or larger) soil chunks and the hazardous fragment areal density requirement (1 hazardous fragment/600 square feet). To be consistent with the primary fragment calculations, the maximum range of the soil ejecta should be used. Examination of the original soil ejecta data from AFWL-TR-74-351 [5] shows that the average ratio between the maximum soil ejecta range and the range of one hazardous ejecta per 600 square feet is 1.9. Therefore, the maximum ejecta radius R_{max} is then

$$R_{max} = 1.9(2 \cdot y \cdot d) = 3.8 \cdot y \cdot d$$

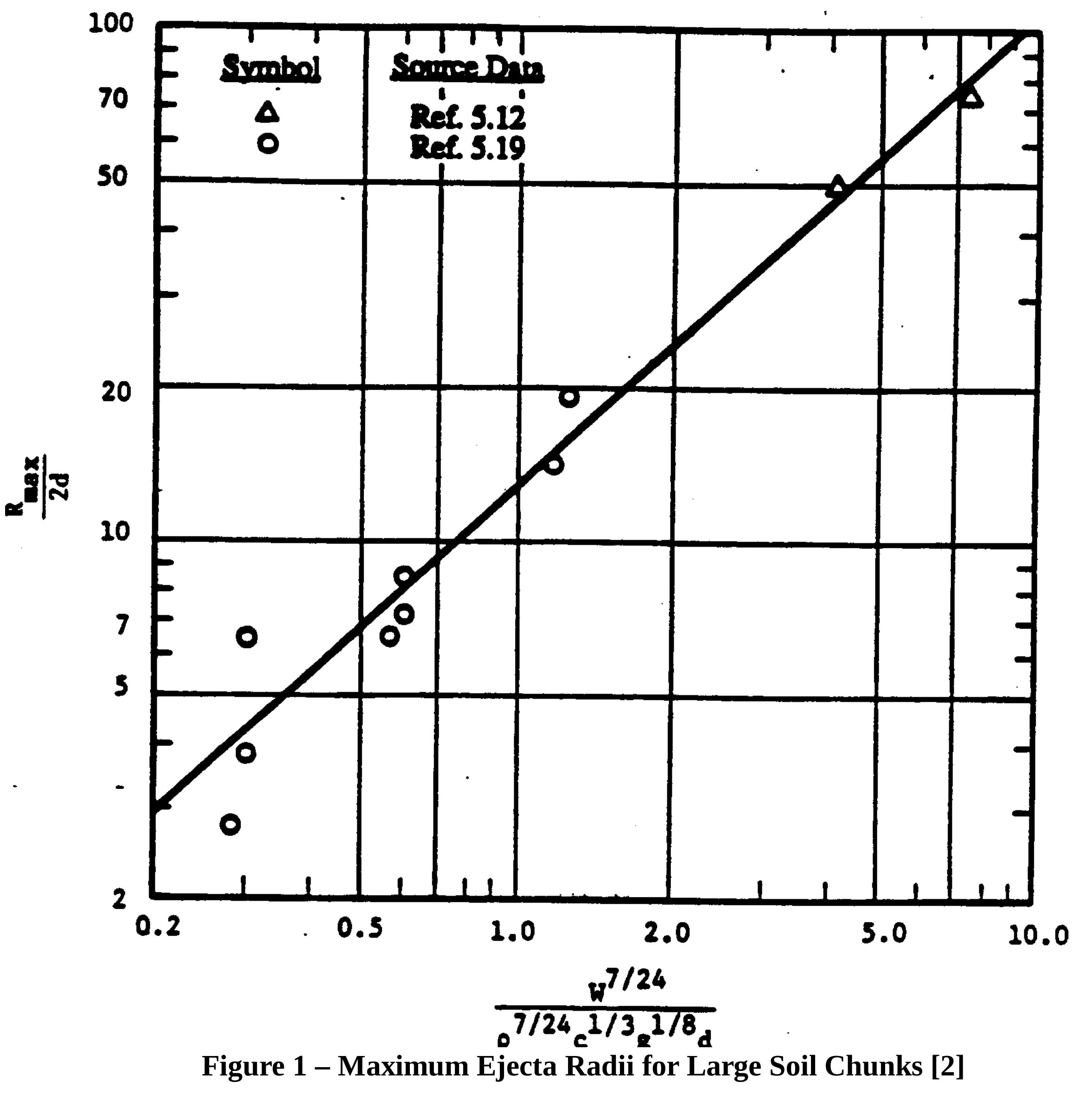

Figure 1 – Maximum Ejecta Radii for Large Soil Chunks [2]

Due to the nature of the equations used in BEM, the calculations will never result in a final fragment velocity and corresponding fragment range of zero. However, where a crater is formed a burial depth may be found where the fragment range will be less than the soil ejecta range. There is no added benefit to burying the munition any deeper until reaching the depth at which a camouflet is formed.

3.0 SOFTWARE DESCRIPTION

3.1 INPUT DATA

The necessary values are input into BEM in an interactive mode. The user is prompted to input the following values.

1) A title identifying the problem.
2) The total net explosive weight (TNT equivalent) in lbs.
3) The depth of burial in feet.
4) The design fragment weight in lbs.
5) The initial fragment velocity in feet/sec.
6) The soil type chosen from a pre-defined list or

    a) the specific weight of the soil in lbs/in^3,
    b) the mass density of the soil in $lb\text{-}sec^2/ft^4$,
    c) and the seismic velocity of soil in ft/sec.

Some commonly found munitions have been analyzed and the explosive weight, initial velocity and maximum fragment weights are shown in Table 1. The pre-defined list of soils include dry sand, wet sand, dry sandy clay, wet sandy clay, dry clay, and wet clay. Average soil properties are used for each of these soil types. Some typical soil data from TM 5-855-1 are shown in Table 2.

3.2 OUTPUT FILE

The results are written to a file called 'BEMOUT'. BEM does not include commands to view or print the results directly.

3.3 SOFTWARE VALIDATION

In order to validate the program, a sample problem was calculated by hand and using the software BEM. Write statements were inserted to print intermediate results. The results of the hand calculations and the BEM calculations are shown in Figures 2 and 3. For a burial depth of 6 ft, both sets of calculations yield a final fragment velocity of 101 ft/sec and a soil ejecta radius of 356 ft. For a burial depth of 8 ft, both sets of calculations show that a camouflet is formed and the final fragment velocity is 31 ft/sec.

Table 1 – Munition Information

Munition	Explosive Type	Explosive Weight (lb)	TNT Equivalent Explosive Weight (lb)	Critical Fragment Weight (lb)	Critical Fragment Velocity (fps)
20 mm M56A4	H761 (RDX)	0.0264	0.0290	0.0006	3183
25 mm M792	HMX	0.0959	0.1199	0.0082	4256
37 mm Mk II	TNT	0.5270	0.5270	0.0295	5758
40 mm MK2	TNT	0.1870	0.1870	0.0331	3605
60 mm M49A3	Comp B	0.4200	0.5376	0.0237	5114
75 mm M48	TNT	1.4700	1.4700	0.1530	3471
81 mm M374	Comp B	2.0900	2.6752	0.0308	6721
105 mm M1	Comp B	5.0700	6.4896	0.2057	4055
155 mm M107	Comp B	15.4480	19.7734	0.6482	3426
4.2 in M3A1	TNT	8.1700	8.1700	0.0787	6391
3 in Stokes	TNT	2.1000	2.1000	0.0436	6189
4 in Stokes	TNT	7.9200	7.9200	0.0782	6336
8 in M106	Comp B	38.8000	49.6640	1.693	3091
4.7 in Mark 1	TNT	6.0700	6.0700	0.5915	3566

USAESCH has been running a test program to determine the thickness of sandbags needed to defeat fragments from a munition on the ground surface. A munition is placed on its side on the ground surface and sandbags are placed around all four sides and the top of the munition with a 6-inch standoff from the munition. The munition is detonated using a perforating shaped charge. Witness screens are used between sandbags to determine if fragments penetrate the sandbag layer and overpressure and noise measurements are taken at several distances from the center of the detonation. Sandbag throw is also measured. At the end of the test program, a full report of these results will be available.

Table 2 – Soil Properties from Explosion Tests

Soil Description	Unit Wt (pcf)	Seismic Velocity (fps)	Mass Density (lb-sec^2/ft^4)	Specific Weight (pci)
Dry desert alluvium and playa, partially cemented	97	3150	3.0124	0.0561
Loose, dry poorly graded sand	90	600	2.7950	0.0521
Loose, wet, poorly graded sand with free-standing water	116	550	3.6025	0.0671
Dense dry sand, poorly graded	104	1100	3.2298	0.0602
Dense wet sand, poorly graded, with free-standing water	124	1000	3.8509	0.0718
Very dense dry sand, relative density = 100%	109	1600	3.3851	0.0631
Silty-clay, wet	123	800	3.8199	0.0712
Moist loess, clayey sand	122	1000	3.7888	0.0706
Wet sandy clay, above water table	123	1800	3.8199	0.0712
Saturated sandy clay, below water table	117	5500	3.6335	0.0677
Saturated stiff clay, saturated clay-shale	125	>5000	3.8820	0.0723

To date, sandbag tests have been completed on five munitions. The results from these tests are compared to the results from BEM in Table 3. The burial depths determined using BEM are approximately twice the required thickness of sandbags from the sandbag tests. Also, where a crater is formed, the soil ejecta range is greater than the sandbag throw. The sandbag tests are run with a standoff between the munition and the sandbag. Therefore, there is not full coupling between the explosive event and the sandbags whereas BEM assumes full coupling between the explosive event and the soil. In addition, the sandbags are larger than the soil ejecta considered in BEM so the drag is larger and the sandbags won't travel as far as the soil ejecta. Also, BEM will never result in a zero fragment velocity and fragment range.

The BEM software produces the same results as when the method is applied by hand. Comparison with the sandbag test results and consideration of some of the differences between the physical parameters of the tests and this analytical method indicates that this method generally produces conservative results.

Table 3 – Primary Fragment Mitigation Using Earth Cover

Munition	Sandbag Tests		Tamped Earth Using BEM		
	Thickness Required to Defeat Fragment (ft)	Sandbag Throw (ft)	Thickness of Earth Cover (ft)	Fragment Range (ft)	Soil Ejecta Range (ft)
155 mm M107	3	200	6	247	356
4.2” M3A1	2	110	4	83	271
105 mm M1	2	120	5	84	N/A*
81 mm M374A1	1.67	110	3	70	197
60 mm M49A3	1	20	2	271	N/A*

*Note: Camouflet is formed

4.0 REFERENCES

1. “TRAJ--A Two Dimensional Trajectory Program for Personal Computers", Minutes of the Twenty-Fourth Explosives Safety Seminar, August 1990, pp. 1853-1879, Montanaro, P.E.

2. DOE/TIC-11268, A Manual for the Prediction of Blast and Fragment Loadings on Structures, February 1992.

3. Army TM 5-855-1, Fundamentals of Protective Design for Conventional Weapons, November 1986.

4. Army TM 5-1300, Structures to Resist the Effects of Accidental Explosions, November 1990.

5. "Near-Surface Cratering Experiments, Fort Polk, Louisiana", AFWL-TR-74-351, U.S. Army Engineers Waterways Experiment Station, November 1975.

6 “Methods for Predicting Primary Fragmentation Characteristics of Cased Explosives”, HNC-ED-CS-S-98-1, U.S. Army Engineering and Support Center, Huntsville, January 1998.

Figure 2 - Sample Problem Hand Calculations

Given: 155 mm M107

Explosive weight = 15.4 lbs Comp B x 1.28 = 19.71 lbs TNT equivalent

Design fragment weight = 0.6482 lbs

Initial fragment velocity = 3426 fps

Dry Sand

Mass density of soil = 3.1367 lb-sec^2/ft^4

Seismic velocity of soil = 1100 fps

Specific weight of soil = .0585 pci

Depth of burial = 6 ft

Calculations:

Is a crater or a camouflet formed?

$X = 4.605+\ln((1.2(19.71)^{.25})/6) = 3.60$

$Y = [6.438+1.398\ln((1.2(19.71)^{.5})/8)]\tanh^5[2.00+0.4343\ln((1.2(19.71)^{.5})/8)]$

$= 3.82$

X < Y Therefore a crater is formed

d = diameter of fragment = $(W_f/0.186)^{1/3} = 1.516$ in

A = presented area of fragment = pd^2/4 = 1.805 in^2

$$k_v = (\frac{A}{W_f}) \cdot (\frac{\gamma_0}{2}) \cdot C_D = 0.0489$$

$V_s = V_0 e^{-12kvR} = 101$ fps

Soil Ejecta

$$x = \frac{(1.2 \cdot 19.71 \cdot 1.7x10^6)^{7/24}}{3.1367^{7/24} \cdot 1100^{1/3} \cdot 32.2^{1/8} \cdot 6} = 1.24$$

$$y = 10^{(0.9 \cdot \log(1.24)+1.11)} = 15.61$$

R_{max} = 3.8 DOB y = 356 ft

Given: 155 mm M107

Depth of burial = 8 ft

Calculations:

X = 3.32

Y = 3.20

X > Y Therefore a camouflet is formed.

V_s = 31 fps

Figure 3 - Sample Problem Results from BEM (File BEMOUT)

BURIED EXPLOSION MODULE (BEM)
155 MM M107 AT 6 FT

Total net explosive weight, lbs = 19.71
Initial fragment velocity, fps = 3426.
Fragment weight, lbs = .6482
Depth of burial, ft = 6.00
Specific weight of soil, pci = .0585
Mass density of soil, lb-sec^2/ft^4 = 3.1367
Seismic velocity of soil, fps = 1100.0000

A CRATER IS FORMED

True crater radius, ft = 20.43
Final fragment velocity, fps = 101.
Start angle for trajectory, deg = 16
Maximum soil ejecta radius, ft = 355.9230

BURIED EXPLOSION MODULE (BEM)
155 MM M107 AT 8 FT

Total net explosive weight, lbs = 19.71
Initial fragment velocity, fps = 3426.
Fragment weight, lbs = .6482
Depth of burial, ft = 8.00
Specific weight of soil, pci = .0585

A CAMOUFLET IS FORMED

Camouflet radius, ft = 3.10
Final fragment velocity, fps = 31.